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Application of the multiple criteria decision-making (MCDM) approach in the identification of Carbon Footprint reduction actions in the Brazilian beef production chain

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A B S T R A C T

Global awareness regarding the effects of Climate Change has led to a more restrictive society and demanding concerned with Greenhouse Gas Emissions associated with consumption. In this context, the livestock sector is seen as a major contributor to various impacts, as it is implemented throughout different climatic zones, with high variations in production and food systems, which, in turn, present direct impacts on productivity and environmental externalities. In this context, the aim of this study was to rank possible improvement actions that allow the reduction of the Carbon Footprint originated from Brazilian beef exports considering multiple criteria, from the identification of the impact profile associated with the final product. Thus, the Carbon Footprint was first estimated considering the production phase, in the Brazilian Central-West, and beef processing and transport until its delivery at three main final export destinations: Rotterdam, Shanghai and St. Petersburg. Subsequently, multicriteria decision-making methods were applied in order to quantify and rank possible improvement actions, with the joint application of the Fuzzy Set Theory and the TOPSIS method. Finally, the criteria are presented in the form of a SWOT (Strengths, Weaknesses, Opportunities and Threats) matrix for each evaluated alternative. The animal production stage represented the main impacts of Climate Change on the product system (over 96% for all export destinations) due to the digestive fermentation of the animals, leading to methane emissions. The option to implement improvement actions for the evaluated productive arrangement, the use of protein-energetic supplementation and pasture fertilization-rotation in the animal production phase, alongside the replacement of road transport units by more modern vehicles in the industrial phase, were identified as alternatives that decrease the impact potential and facilitate the animal production phase. In this sense, the results point to possible improvements that, in addition to presenting low restrictions for implementation, can significantly reduce the beef Carbon Footprint. Improving Brazilian efficiency in terms of Carbon Footprint in this production chain can, in addition to provide a strategic differential concerning production and commercialization, contribute to reduce environmental impacts resulting from the sector at a global level. However, it is necessary to search for measures that facilitate the implementation of these actions, mainly at the rural producer level, considering both technical aspects and the qualification, training, consulting and financial aspects, such as credit and

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subsidies, improving the environmental performance of this arrangement with a view to balancing it with the other dimensions.

1. Introduction

Global awareness regarding the potential effects of Climate Change has led to a more restrictive and demanding society concerned with Greenhouse Gas (GHG) emissions associated with consumer goods. This behavior also extends to certain foodstuffs, such as cattle beef which, in addition to leading to significant methane (CH_4) and dinitrogen oxide (N_2O), emissions, makes regular use of export activities to supply market demands (Steinfeld et al., 2006; Wiedemann et al., 2015). According to the US Department of Agriculture the world's cattle herd has exceeded 1 billion animals (USDA, 2016). Livestock activities take place throughout different climatic zones, with high variations in the production and feeding systems, which generate direct impacts on productivity and environmental externalities (Veysset et al., 2014). These characteristics make the sector responsible for about 15% of the planet's accumulated GHG emissions, with approximately 44% of this total being CH_4 resulting from cattle enteric fermentation (Gerber et al., 2013; Ruviaro et al., 2016). Conversely, the livestock sector exhibits high rates of carbon removal from the air, in the form of carbon dioxide (CO_2), due to absorption by pastures, expected to range from 45 to 60 t C.ha^{-1} in 20 years (de Oliveira Silva et al., 2016).

Brazil is an important player in the international livestock segment, comprising about 22% of the world's cattle population (216 MM heads) and producing 15% of all beef (9.3 MMt) consumed in 2016. Thus, the country became the major exporter of this product concerning monetary value during this period, with a revenue of US$ 5.5 billion (USDA, 2016). In this scenario, obtaining satisfactory environmental indices, especially in terms of Carbon Footprint (CF), can provide Brazilian producers with a strategic differential that allows them to maintain (or increase) holdings in their operational markets, as well as occupy niches currently dominated by competitors.

A methodical approach to achieving this objective consists in determining beef-associated CF, identifying potential CF sources, and proposing improvement actions that may mitigate or even eliminate its influence. In order lead to effective actions in this regard, it is desirable to obtain a consistent diagnosis that quantitatively describes Climate Change impacts associated with the supply chain of the product under a life cycle perspective, from the preparation of livestock resources (e.g. pasture), to final meat distribution in the consumer market, including the cattle raising, slaughtering, and meat processing steps.

For many academics, analyzing livestock production from a life-cycle point of view allows for the understanding and identification of potential GHG emission sources GHG (Dick et al., 2015; Florindo et al., 2017; Mazzetto et al., 2015; and Ruviaro et al., 2016). On the other hand, these authors also consider that any improvement proposals to be implemented in this productive chain should be evaluated in a broad, systemic and interconnected way, due to the dependency relations established in the beef cycle, based on trade-offs between these same improvement actions and their environmental interactions. A robust, and at the same time conceptual, way of performing such verifications is through the application of Multiple criteria Decision-Making (MCDM) methods.

In general, the MCDM methods consist of approaches capable of classifying, comparing, identifying and selecting solutions to complex problems from a limited number of predetermined alternatives. These techniques are effective in dealing with inaccuracies and uncertainties, as well as conflicting criteria that appear during the decision-making process (Tzeng and Huang, 2011). The application of MCDM methods involves the identification of possible solution and criteria capable of organizing these alternatives according to the expectations of the decision to be made. However, in addition to being qualitative, these elements are usually subject to imprecision, and even to a certain degree of subjectivity, due to the use of value judgments for their formulation. According to Herva and Roca (2013), an increasingly frequent procedure used to mitigate such distortions in opinion polls consists of the Fuzzy Set Theory. Fuzzy systems were first described by Zadeh (1965) as being a set of language and mathematical equivalence rules able of generating accurate representations of the behavior of real world systems.

Once the alternatives and evaluation criteria have been identified, preference ordering methods can be used to select the most appropriate option of the set, taking into account its performance along with the multiple criteria applied for the analysis (Kahraman, 2008). Ordering methods can be classified into two main groups: (i) those based on utility theory, such as the Analytic Hierarchy Process (AHP), Technique of Order Preference by Similarity to an Ideal Solution (TOPSIS), Simple Multi-Attribute Rating Technique (SMART), *VlseKriterijumska Optimizacija I KompromisnoResenje* (VIKOR); and (ii) Outranking methods, such as Preference Ranking Organization METHods for Enrichment Evaluations (PROMETHEE), Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) and the Elimination Et Choix Traduisant la Réalité (PROMETHEE ELECTRE). MCDM selection and application procedures should be handled with care, since the application domain of each method in terms of problem-solving is conditioned to its design philosophy (Cinelli et al., 2014; Penadés-Plà et al., 2016).

Taking into account this context, the present study proposes the application of MCDM techniques in the identification of potential improvement actions allowing for decreases in the Brazilian beef export CF. In a broader perspective, which transcends the limits of the market relations described above, the search for better FC indices regarding the Brazilian cattle livestock sector could result in important collective environmental gains. According to Gerber et al. (2013), as emerging economies are dependent on natural resources to maintain their productive chains active, the adoption of efficient management practices for these systems, especially the agriculture and livestock sectors, could reduce global GHG emissions by up to one third.

2. Materials and methods

In conceptual terms, this research was structured applying two approaches: (i) a case study, adopted with the purpose of understanding in detail the behavior of the evaluated phenomenon within its real context; and (ii) data modeling, applied within the perspective described by Yin (2014), to provide an abstraction of all significant and relevant elements, attributes and relationships of a real situation, and represents them by recreating their context. In practical terms, the method applied in this study comprises three steps.

In the first step, the CF associated with the Brazilian beef export

was determined. This action, materialized in the form of a case study, began with the Definition of the Product System Model, comprising the following actions: (i) information gathering from technical literature in order to characterize the beef production chain in Brazil; (ii) identification of producer regions and establishment of medium technological and operational models for animal husbandry and industrial meat processing; (iii) specification of transport modes and network distribution of livestock and meat within the country; and (iv) definition and application of objective criteria for the selection of the most frequent product destinations and, from this, the identification of the means of transport, routes and distances traveled in these processes. The product system model was formulated in accordance with the concept of Life Cycle Thinking, with a 'cradle-to-final destination' scope, which considered all anthropic actions of the productive process, from animal breeding to the delivery of the final product to the main export destinations.

The Brazilian Midwest region was selected to model the livestock breeding and slaughter stages, due to its significant contribution to the country's accumulated production. In 2015 this region accumulated 73 million head of cattle (34% of the country total). Of this total, 40% were concentrated in the state of Mato Grosso (MT), the largest national producer, while the rest was distributed equally between Mato Grosso do Sul (MS) and Goiás (GO) (IBGE, 2016). The Life Cycle Inventory (LCI) was based on the quantification of GHG emissions from the beef production chain. The sum of GHG emissions were adjusted to the functional unit defined for the study, of '1.0 kg of boned exported beef'. To develop the LCI, any multifunctional processes in the product system were treated by allocation procedures. To estimate the product CF, GHG emissions were expressed in terms of contributions to Climate Change through IPCC AR5 coefficients for 100 years of pollutant retention time in the atmosphere (Myhre et al., 2013).

The diagnosis generated in this stage allowed not only to understand the accumulated CF value of the final product for the conditions defined for model structuring, but also to identify impact generation points concerning Climate Change.

The second step consisting in proposing performance improvement actions and criteria for comparing these solutions. Taking into account the diagnostic results, questionnaires in which technology-based solutions and technically feasible and economically viable practices and production procedures have been elaborated. These documents were then submitted to livestock breeding and meat processing specialists. Regarding the alternative selection criteria, it was agreed that they should meet at least one of the following requirements: (i) exhibit the potential to reduce GHG emissions; or (ii) be able to rank solutions within the proposed universe of possibilities. The questionnaire result comparison was performed through a MCDM technique comprising a Fuzzy Set Theory, a mathematical method used to approach the imprecisions and uncertainties inherent in human judgments during decision-making processes, which is driven by linguistic terms and degrees of adherence (Mahmoodzadeh et al., 2007; Tzeng and Huang, 2011). In cases of high disparity among alternatives for a certain criterion, we opted to rank the potential improvement actions. This procedure was carried by TOPSIS (Technique for Order Preference for Similarity to the Ideal Solution), another MCDC technique.

Finally, in the third step of the method, the normalized and weighted outcomes from the decision-making matrix have been expressed as a SWOT matrix. This procedure was applied with the purpose of facilitating the understanding of the criteria associated to each alternative solution, and thus, better support the discussions originating from those results.

2.1. Life cycle modeling

Herein, the production chain of Brazilian beef export was composed of five stages: (i) livestock raising, (ii) cattle transport from the farm to the slaughterhouse, (iii) meat processing, (iv) product transport to the port of origin, and (v) transport to the port of destination (Fig. 1). Technical and operational aspects associated with this arrangement are described below, taking into account the average technology practiced in the country for each stage.

2.1.1. Raising livestock

The meat cattle industry in Brazil comprises a large variety of animal breeding, management forms, and production systems (Florindo et al., 2017; Ruviaro et al., 2016, 2015). In this study, cattle ranching was modeled using primary data collected from a livestock enterprise located in the city of Iguatemi (MS), referring to the slaughter of 400 animals from 2007 to 2014. The production system used for raising livestock is intensive grazing, typical of the area. The animals, a cross between the Nelore and Abeerden Angus breeds, are fed in *Brachiaria brizantha marandú* pastures until the finishing phase, when they begin to consume *Brachiaria brizantha xaraés*. Throughout the fattening cycle, non-protein mineral supplementation is provided. As a result, the animals reach an average of 570 kg live weight after 36 months. Each animal ingests 58% of total digestible nutrients (TDN), with 53% digestibility of dry matter intake, and 9.1% crude protein. More information about the description of the evaluated production system can be obtained in Florindo et al. (2017).

GHG emissions due to enteric fermentation, waste management, pastures, and fertilizer use were calculated by the IPCC Tier 2 approach (IPCC, 2006). Environmental burdens associated with livestock externalities (pasture, feed, mineral supplementation, fertilizer use and fossil fuels) were taken into account as full life cycle; i.e., a life-cycle scope that includes natural resource extraction, the manufacture of each good, and their use in the animal rearing process until they reach slaughter conditions. The operations and procedures practiced in rural properties consistently describe the average livestock technology applied in the Brazilian Midwest.

2.1.2. Transport from the farm to the slaughterhouse

The animals are slaughtered in a plant in the city of Naviraí (MS) 45 km distant from the farm. The transport takes place in diesel-powered vehicles (autonomy of 0.31 L/km) with a carrying capacity for 40 live animals. The effects in terms of Climate Change of fuel combustion were estimated by applying an impact factor (IF = 2.48 kg CO_{2eq}/L diesel) obtained from the 2nd National Inventory of Atmospheric Emissions by Road Automotive Vehicles (MMA, 2014).

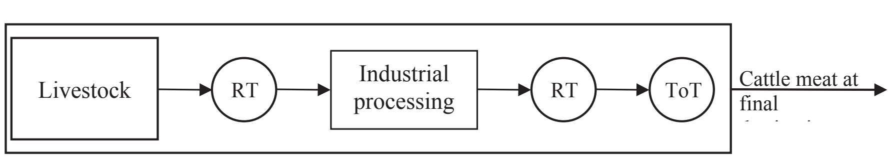

Fig. 1. Brazilian meat production chain from 'cradle-to-final destination'. Notes: RT – Road transportation; ToT – Transoceanic transportation.

2.1.3. Meat processing

The animal slaughter and meat processing stages are traditional and well established practices in Brazil; because of that, they could be described through secondary data collected from Pacheco and Yamanaka (2006). Energy expenditures represent the main source of impact at the meat processing stage (Wiedemann et al., 2015). Emission factors and energy conversion values were obtained from baseline reports provided by Rosa et al. (2002). For the modeling effect, it was assumed that the thermal meat processing demand was supplied from charcoal burning in boilers, due to the prevalence of this energy source over others, including those of fossil origin, in industrial processes in central Brazil (Wiecheteck, 2009).

Meat processing is characterized as a multifunctional process. Therefore, in addition to the meat itself, other by-products, such as leather, blood and bone meal, are generated in this stage. In the present case, we chose to apply the allocation procedure by economic criterion, in order to distribute the environmental loads accumulated up to this stage of the production chain. This decision was based on the fact that meat exhibits the greatest economic representativeness among the generated co-products. A slaughterhouse manager was consulted in order to determine the marketing value of all the co-products obtained from cattle slaughter. As a result, over 84% of the total impact was attributed to beef.

2.1.4. Transporting from the slaughterhouse to the port

Approximately 50% of the Brazilian beef exported abroad in 2015 left the country from the Santos Port (SP) (ALICE WEB, 2016). Therefore, this location was selected as the trans-oceanic transportation origin for the model. It was also assumed that the distance slaughterhouse-port (1050 km) would be traveled by road in 27.0 t load capacity vehicle. The GHG emissions originate from diesel burning for load refrigeration and vehicle movement. Under these conditions, an average total diesel consumption of 0.36 L/km was estimated.

2.1.5. Transport from the port of origin to the port of destination

The determination of the ports of destination was based on the export profile of Brazilian meat in 2015, established by official data collected from the Alice Web system (ALICE WEB, 2016). The survey indicated three directions: (i) Shanghai (CN), due to the growth of Brazilian exports to China in 2015, and its proximity to Hong Kong; (ii) St. Petersburg (RU), as Russia has been the main export focus for this product in the last five years; and (iii) Rotterdam (NL), the gateway of Brazilian meat to Europe. The distances between ports were estimated by actual data (SeaRates, 2016). The trans-oceanic transport CF was determined using the emission factor (EF = 22.0 g CO_2/km.t) proposed by Webb et al. (2013) to describe the environmental performance of trans-oceanic cargo shipments.

2.2. Procedure for performance improvement actions

The proposed strategy to identify improvement actions for the beef production chain was composed of three actions: (i) questionnaire application to beef production, distribution logistics, and meat processing specialists; (ii) quantification of information obtained through the application of Fuzzy Set Theory and ranking of the most effective alternatives by an MCDM technique; and (iii) the creation of a SWOT matrix, in order to classify the same proposal according to internal and external environments.

As a rule, the beef production chain in Brazil is horizontal; the activities linked to livestock production are controlled by the rural producers, while slaughtering, meat processing and transportation from the farm to the final destination are industrial responsibilities. Due to this structure, we decided that the process of identifying potential improvements should involve specialists from different segments of the production chain. Stakeholders were interviewed from each subgroup, i.e. rural producers and industry professionals, through a structured questionnaire, which specified in advance a set of possible alternatives for improvement. This procedure was adopted to allow for the answers to be comparable with each other and with previously established criteria.

The stakeholder selection was conducted from a non-probabilistic sample by accessibility. The use of this approach resulted in contact with two slaughterhouses and their respective transporters, as well as the cattle ranchers who provide cattle for slaughter. The group of respondents who took part in the study was supplemented by specialists from three accessory companies in the field of cattle raising.

A set of eight different alternatives for cattle raising, formulated from the most common herd production systems in Brazil, were presented to rural producers. Conversely, for industrial stakeholders, possible improvement solutions in two areas were suggested: (i) livestock (farm − slaughterhouse), and meat (slaughterhouse − port) transport review; and (ii) technological process updates, especially with regard to the utility provision. The two classes of alternatives for potential CF system improvement are indicated in Table 1.

The criteria selected for the comparison of alternatives are indicated in Table 2. Those referring respectively to 'Early animal slaughter' (CA1) and 'Energy Efficiency' (CI1) meet the requirements for GHG emission reductions. Conversely, the criteria dealing with 'Deployment costs' (CI2) and 'Availability of financing

Table 1
Defining alternatives for performance improvement.

Stage	Improvement alternative		Code
Animal Production	Adoption reference system		AP1
	Adoption of semi-confined System		AP2
	Adoption of confined System		AP3
	Supplementation protein/energy		AP4
	Fertilization and rotation of pastures		AP5
	Replacement of pastures by *Panicum* sp.		AP6
	Agricultural and livestock integration		AP7
	Integration of crop-livestock-forest		AP8
Industry	Transport: farm − slaughterhouse	Fleet update	ITF1
		Use of vehicles with a higher load capacity	ITF2
	Slaughterhouse	Replacement of boiler with similar equipment with higher thermal efficiency	IF1
		Replacement of refrigeration compressors by may energy efficiency equipment	IF2
		Use of renewable energies	IF3
	Transport: Slaughterhouse - port	Fleet update	ITP1
		Use of vehicles with a higher load capacity	ITP2
		Adoption of multimodal transport (road and rail)	ITP3

Table 2
Definition of criteria for comparison of proposed alternatives.

Stage	Criteria	Code
Animal Production	Early slaughter of animals	CA1
	Use of non-renewable inputs	CA2
	Grain dependence for food	CA3
	Productivity animal per hectare	CA4
	Deployment constraint analysis	CA5
	Availability of financing lines	CA6
Industry	Energy Efficiency	CI1
	Deployment Cost	CI2
	Deployment constraint analysis	CI3
	Availability of financing lines	CI4

Table 3
Definition of language variables.

Language Terms	Scale	Function
Much Lower	(0,0,3)	Semi-trapezoidal
Lower	(0,3,5)	Triangular
Medium	(2,5,8)	Triangular
Superior	(5,7,10)	Triangular
Higher superior	(8,10,10)	Semi-trapezoidal

lines' (CI4) complies with the principle of alternative ranking.

The criterion of 'Deployment constraints analysis' had different objectives for the animal production (CA5) and industry (CI3) stages. In the case of CA5, the following restrictions were established: system implementation costs; actual implementation time; the work force involved; and the training and capacity building that would be necessary so the enterprise could operate at high efficiency after the implementation of actions aiming to reduce CF. In CI3, the cost was not defined as a restriction because a specific criterion for its measurement (CI2) was already established.

In approaching the export beef production chain from this perspective, the questionnaire responses were coded as Fuzzy linguistic variables, like 'higher', 'superior', 'medium', 'lower' and 'much lower', and quantified into triangular and semi-trapezoidal relevance functions (Table 3).

The Fuzzy system inference process was performed by the Takagi-Sugeno method (Tzeng and Huang, 2011). For variable standardization, all criteria were converted to 'greater/better', due to the existence of 'greater/better' and 'smaller/better' criteria. Thus, the greater the value indicated in the decision-making matrix, the better the criterion evaluation. A decision-making matrix was generated the application of Fuzzy Set Theory.

The oscillation in the scoring of the potential solutions among the evaluated criteria were treated by TOPSIS. Developed by Hwang and Yoon in 1981, this approach consists of a compensatory aggregation method that compares a set of alternatives. In this regard, TOPSIS is applied for score normalization and weighing and estimates of the geometric distance (deviation) between each alternative under analysis and the so-called 'ideal alternative' (Mahmoodzadeh et al., 2007). The better alternative is considered the one that simultaneously records the lowest deviation from the ideal positive alternative and the highest deviation from the ideal negative alternative (Onat et al., 2016; Tzeng and Huang, 2011).

The ranking of the most effective alternatives was initiated by decision matrix [A], comprising alternatives *(i)* and criteria *(j)*. Matrix [A] was then normalized, originating matrix [R]. The linear normalization of the data was adopted in order to avoid possible outliers. A weighting was performed once this stage was reached. The effects of this procedure were not, however, noted for the case in question, due to the decision to assign unit weights to all criteria. In the next step, the highest possible positive value (A^+) and the lowest possible negative value (A^-) were determined, respectively, for each criterion. These results were then used to calculate and sum the standard-deviations (minimum: d_i^- and maximum: d_i^+) for each criterion, in relation to A^+ and A^- (Equations (1) and (2)):

$$d_i^+ = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^+\right)^2} \tag{1}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^-\right)^2} \tag{2}$$

The process was finally concluded by estimating the approximation coefficient *($C^+{}_i$)* of each solution in relation to the ideal and negative alternatives, (Equation (3)):

$$C_i^+ = \frac{d_i^-}{\left(d_i^+ + d_i^-\right)} \tag{3}$$

The $C^+{}_i$ values were ranked in descending order, to provide a broader picture of all alternatives under analysis. The possibility of providing results for each alternative is one of the benefits brought by the TOPSIS method, compared to other MCDM techniques (Onat et al., 2016).

To facilitate the understanding of the different criteria of each improvement alternative, the decision-making matrix was then described in the form of a SWOT matrix. This approach is one of the most popular analytical methods used in strategic analyses, assessing both strengths and weaknesses in the internal environment and opportunities and threats in the external environment (Štěrbová et al., 2016). SWOT analyses are frequently used to acquire knowledge regarding a certain situation and subsequently designing strategies for its improvement (Nikolaou and Evangelinos, 2010).

Table 4
Contribution by GHG and sources of emission from the livestock stage.

Emissions	Contributions (kg/Cattle head)		
	CH_4	N_2O	CO_2
Enteric fermentation	168	0	0
Digestion of waste	1.54	9.60E-01	0
Nitrogen fertilizers	0	1.00E-02	0
Fuels (diesel)	0	0	103
Total	**169**	**9.70E-01**	**103**
Impact Factor (kg CO_2 eq/kg GEE)	28	265	1.00
Impact per precursor (kg CO_2 eq/cattle head)	4747	257	103
Total impact (kg CO_2 eq/cattle head)	**5107**		

*IPCC AR5-100 years.
Source: Myhre et al. (2013).

3. Results

3.1. Carbon footprint (CF)

3.1.1. Raising livestock

The GHG emissions and their impacts in terms of Climate Changes generated by raising livestock are displayed in Table 4. The main emission source at this stage is enteric fermentation, the result of the natural digestion processes in ruminants. Part of the energy from consumed food is lost, resulting in CH_4 emissions (de Vries et al., 2015; Florindo et al., 2017). A discrete contribution originated from the digestion of manure from pasture decomposition has also been observed. In terms of contributions such as

GHG, the process manifests itself as atmospheric CH_4 and N_2O emissions. In addition, N_2O releases due to the addition of nitrogen fertilizers for pasture fertilization are also observed. Finally, CO_2 releases from diesel fuel burning in agricultural machines used to establish pastures are also noteworthy.

Since the animals reach, on average, 570 kg of body mass under slaughter conditions, the obtained results account for a Brazilian livestock CF of 8.96 kg $CO_{2\ eq}$/kg produced live weight. About 93% of this total is concentrated in the enteric fermentation process, which is highly influenced by the technological procedures and operational practices exercised during livestock rearing.

3.1.2. Transportation farm – slaughterhouse

Table 5 describes data on transport specifications, GHG emission factors, and impacts associated with this beef production chain stage.

Although the contribution associated with transporting animals to the slaughterhouse (3.42 g CO_2/kg live load) is secondary compared to that calculated for animal production, this result is noteworthy due to the intervention of two variables: (i) the live mass carried during each shift, which influences the estimation of vehicle autonomy; and (ii) the distance that the vehicle must travel (90 km), assuming that the total distance also includes its return to the origin (farm). The option by road transport potentialized the previously underlined effects, since the displacement becomes cattle exclusive. This situation avoids any possibility of reducing GHG emissions from the beef production process by the allocation of environmental loads with other goods.

3.1.3. Meat processing

The slaughterhouse CF in terms of the amounts of electrical and thermal energies consumed in the process is plotted in Table 6. Heat, which represents the main contribution, is derived from charcoal burning in boilers, while electricity is used for lighting and driving machinery and equipment, with the cooling chamber being the main consumer.

Heat generation is the main impact source at this beef production chain stage since, in addition to its specific demand exceeding four times that of electricity, the CO_2 emission factor due to charcoal burning is about twelve times higher than that of electricity. Because of this, thermal energy consumption accrues 98% of the total process impacts. Table 7 describes the effect of the multifunctionality treatment process for meat processing and the conversion of live weight into the amount of boned meat. This procedure adjusts the units for the calculated emissions and impacts for each stage to the reference flow established for this study.

The option by allocation assumes that all accumulated environmental burdens up to the stage where a multifunctional situation is established (and, hence, their resulting impacts) are weighted according to a transparent and justified criterion (ISO, 2006). In this case, the application of this methodological procedure totaled 7.56 kg $CO_{2\ eq}$/kg body weight. However, taking into account the operational income of the slaughter carcass (53%) and the conversion of that meat into boned meat (81%), which together make up the overall yield of the meat preparation, the cumulative impact up to this stage reaches 17.8 Kg $CO_{2\ eq}$/kg boned meat.

Table 6
Impacts specific to slaughtered animals.

Description	Energy	Heat	Total
Specific consumption (kwh/head of cattle)	40	160	200
Emission factor (g CO_2/kwh)	32.2	395	–
Total emission CO_2 (kg/head of cattle)	1.29	63.2	64.5
Total impact (kg CO_2 eq/head of cattle)	**64.5**		

Source: Pacheco e Yamanaka (2006).

3.1.4. Slaughterhouse - Port of Santos

Transportation between the slaughterhouse and the Port of Santos occurs exclusively by road, according to the conditions described in Table 8.

The obtained results indicate that the CF (68.9 g $CO_{2\ eq}$/kg boned meat) is even more conditioned by the mode of transportation employed and the traveled distance (2100 km) than that for the farm– slaughterhouse displacement.

3.1.5. Transport: Prot of Santos - port of destination

Table 9 describes the traveled distances and the associated impacts of each trans-oceanic displacement. As expected, these mobilities represent the main impact sources among the transports that occur throughout the product system, mainly due to the distances between the cargo point of origin and final destination.

By expressing the CO_2 emissions for all these displacements, we observed that trans-oceanic mobility registers the best specific emission index of the whole series. The value obtained from Webb et al. (2013) and applied for this estimate is lower than those calculated for slaughterhouse–port (32.8 g CO_2/(km.t) and farm-slaughterhouse (38.0 g CO_2/(km.t) transports. Although the autonomy of the truck used to transport live cargo (3.20 km/L) seems to be higher than that achieved by the truck that distributes boneless meat (2.80 km/L), the latter result was obtained for 27.0 t of cargo, while the former was calculated for 20.4 t.

3.1.6. Carbon Footprint (CF) for exported Brazilian beef

Table 10 display the individual CF results for each production chain stage and the calculated totals for exported Brazilian beef. The performance of the product delivered to Shanghai (CN) is slightly more aggressive than those for meat distributions to Rotterdam (NL) and St. Petersburg (UK), which are equivalent.

The variability between the totals is exclusively due to the contributions provided by trans-oceanic transports, whose participation is discrete (1.2–2.5%) in terms of accumulated values. The meat processing contribution was stable and not expressive (~1.4%). Animal production continues to show significant CF participation rates (>96%), despite the final destination of the product, becoming,

Table 5
Emission factors and specifications for the transport of live animals.

Description of the vehicle		Performance and emission factors	
Vehicle class	Cart	Shipping distance (km)[a]	90.0
Fuel	diesel	Vehicle range (km/L)[b]	3.20
Engine power (HP)	310	Total diesel consumption (L)	28.1
Uploaded load (amount)	40	Specific emission of CO_2 (kg/L)	2,48
Average weight (kg/cattle)	510	Total emission of CO_2 (kg)	69.7
Total weight (kg)	20,400	Specific emission (g CO_2/kg Live load)	3.42

[a] Considering the round trip.
[b] Average consumption between the going (empty vehicle) and the return (vehicle loaded).

Table 7
Treatment of multifunctionality in meat processing by economic allocation.

Steps	Impact(*) (kg CO_2 eq/kg)	Economic allocation		Conversion: live weight → boned meat	
		By-products	Cattle meat	Production Yield (%)	Impacts(**)
		AF (**) = 15.6%	AF = 84.4%		(kg CO_2 eq/kg)
Livestock	8.96	1.40	7.56	43	17.6
Transport	3.69E-03	5.76E-04	3.11E-03		7.23E-03
Slaughterhouse	1.26E-01	2.00E-02	1.06E-01		2.47E-01
Total Impacts	6.36	9.93E-01	5.37	–	17.8

Observations: (*): estimated impacts (/kg live weight); (**): estimated impacts (/kg boned meat); AF: Allocation factor.

Table 8
Emission specifications and emission factors for boned meat.

Description of the vehicle		Emissions	
Vehicle class	Cart	Vehicle range (km/L)	2.80
Fuel	diesel	Diesel consumption (L):	750
Engine power (HP)	380	Specific emission of CO_2 (kg/L)	2.48
Uploaded load	Container 40 feet	Total emission of CO_2 (kg)	1860
Total weight (kg)	27,000	Specific impact (g CO_2 eq/kg boned meat)	68.9
Shipping distance (km)	2100		

Table 9
Ports of destination, distance traveled from the Port of Santos (BR) and impacts associated with each transoceanic transport.

Port of destination	Distances (km)	Impacts (g CO_2 eq/kg boned meat)
Rotterdam (NL)	10,491	226
Shanghai (CN)	21,442	461
St. Petersburg (RU)	12,415	267

Observation: Considering the emission factor EF = 22.0 g/(km.t) (Webb et al., 2013).

Table 10
Carbon Footprint of Brazilian beef exports characterized by final destination.

Supply chain	Carbon Footprint (g CO_2 eq/kg boned meat)		
	Rotterdam (NL)	Shanghai (CN)	St. Petersburg (RU)
Livestock	17,581	17,581	17,581
Slaughterhouse	247	247	247
Transport			
Farm – Slaughterhouse	6.71	6.71	6.71
Cold store – Porto of Santos	68.9	68.9	68.9
Santos – Rotterdam	226		
Santos – Shanghai		461	
Santos – St. Petersburg			267
Total	**18,130**	**18,365**	**18,171**

therefore, the main focus for improvement actions proposals.

3.2. Actions for potential improvement of the performance of analysis

3.2.1. The Fuzzy system

As described in section 2.2, the productive arrangement under analysis was divided between 'animal production' and 'industry' groups. The processes that constitute animal production are interdependent, making it difficult to evaluate an isolated strategy for improvement (e.g. the substitution of a mineral supplement in livestock diet).

As a result, the main systems used to produce meat cattle in the country were compared as potential improvement alternatives for animal production. Table 11 presents the decision-making matrix elaborated after the application of the Fuzzy system inference process regarding farmer opinions in response to the structured questionnaires.

Table 11
Decision matrix of the animal production phase after application of the Fuzzy inference systems process.

Alternatives	Criteria					
	CA1	CA2	CA3	CA4	CA5	CA6
AP1	3.85	8.75	10.0	3.45	8.75	5.35
AP2	8.00	6.25	5.25	7.75	5.25	5.35
AP3	9.00	3.45	2.15	9.75	2.15	5.85
AP4	7.25	7.75	6.25	5.75	9.00	4.35
AP5	5.75	4.75	9.75	6.25	9.00	5.25
AP6	5.25	4.85	9.75	4.75	5.75	6.75
AP7	8.75	3.85	9.00	8.25	3.95	7.75
AP8	5.85	3.85	9.00	5.75	3.45	8.25

Regarding the animal production stage, a significant variation in all evaluated criteria was observed, due to the different beef production system characteristics presented for specialist appreciation. The activities that integrate the industrial stage of the production chain, however, are not interdependent. This allowed for a verification of the specific effects of each proposed strategy. In the industrial phase, two criteria (CI1 and CI4) presented less amplitude in the results, and, thus, CI2 and CI3 were more representative in the decision-making process (Table 12).

3.2.2. TOPSIS

In view of the significant score variations between the criteria

Table 12
Industry decision matrix after Fuzzy inference systems.

Alternatives	Criteria			
	CI1	CI2	CI3	CI4
ITF1	7.71	8.96	9.17	8.33
ITF2	6.67	7.50	4.25	8.54
IF1	7.08	2.75	2.42	8.75
IF2	7.50	3.58	4.67	8.75
IF3	9.58	2.42	2.75	7.92
ITP1	7.71	8.13	8.96	8.96
ITP2	6.67	5.42	4.25	8.96
ITP3	9.17	3.17	2.42	8.13

Table 13
Values of minimum deviations (d_i^-) and maximum (d_i^+) and coefficient of proximity (C_i^+) for each solution.

Stage	Alternatives	d_i^-	d_i^+	C_i^+
Animal Production	AP1	1.689	0.932	0.644
	AP2	1.482	0.812	0.646
	AP3	1.453	1.283	0.531
	AP4	1.620	0.764	0.680
	AP5	1.626	0.775	0.677
	AP6	1.470	0.894	0.622
	AP7	1.701	0.816	0.675
	AP8	1.479	0.997	0.597
Industry	ITF1	1.675	0.208	0.889
	ITF2	1.326	0.640	0.674
	IF1	1.116	1.044	0.516
	IF2	1.221	0.805	0.602
	IF3	1.222	1.018	0.545
	ITP1	1.651	0.218	0.883
	ITP2	1.245	0.732	0.629
	ITP3	1.215	0.985	0.552

presented by the alternatives, the TOPSIS method was applied for ranking. This was conducted from the d_i^-, d_i^+ and C_i^+ from each alternative (Table 13), measured in relation to the ideal alternative obtained for each criterion.

Regarding the animal production stage, the AP4 (protein-energetic supplementation), AP5 (fertilization and pasture rotation) and AP7 (crop-livestock integration) performances are worth mentioning, since they displayed the highest approximation coefficient values among the alternatives. These results contrast with those for AP3, whose high scoring amplitudes resulted in the lowest C_i^+ of the whole solution series. While the prevalence of AP4 and AP5 was due to equilibrium, in order to obtain intermediate values for all decision-making matrix criteria, AP7 was qualified as a promising solution due to the highest d_i^- and, at the same time, one of the lowest d_i^+ values. This is important, as the improvement action proposals for AP7 carried out under CA2 and CA5 criteria may impose a decrease of their proximity coefficient and, therefore, improve their position in the general planning.

In the industrial stage, C_i^+ amplitude was influenced by the scores that improvement solutions reached applying the CI2 and CI3 criteria. Thus, ITF1 (update of the fleet of live animal transport vehicles) and ITP1 (update of the meat transport fleet processed up to the Port of Santos), whose C_i^+ values totaled 0.889 and 0.883, respectively, are presented as the best proposals in this situation. In addition to greater efficiency in the use of fossil fuels, cases of few restrictions for implementation and good availability of financing lines are also possible. The remaining six solutions scored significantly lower, while IF2 (replacement of refrigeration compressors) was the best alternative for the slaughterhouse.

4. Discussion

4.1. Carbon Footprint of exported Brazilian beef

Although the CF calculated by Wiedemann et al. (2015) for meat manufactured in Australia and distributed in the United States presents between 29% and 50% more cumulative impact in terms of Climate Change than in the present case, the livestock share in that chain (~93%) is similar to that estimated for the Brazilian product. A reversal of contributions concerning industrial processing and transportation is observed, however. In the case of Australian meat, these factors represent respectively 4.2% and 3.4%, due to transport means adopted and the distance traveled by the product to the US. In addition, the cumulative impact differences can be justified due to the Australian system, which presents feedlots with higher consumption of grains and fossil fuels.

Both results agree with the observations reported by Gerber et al. (2013), that livestock farming accounts for 94% of the impacts of meat production worldwide. The stratification of these totals indicates, however, a divergence between the general result and that calculated for the Brazilian product. In global average terms, about 48% of the impacts associated with animal production originate from food manufacturing (pasture and supplements), while 10% comes from waste treatment and no more than 42% originates from enteric fermentation. In the case of Brazilian meat, enteric fermentation is dominant, accounting for 92% of the Climate Change impacts that occur in raising livestock (Table 4). Waste digestion is the next on the list, participating with 5.8%, while food production provides the lowest contribution, composed almost entirely of CO_2 from diesel burning. The production system that currently prevails in Brazil, of the extensive type, with feeding based mainly on pastures and, therefore, with little need of external nutrition supplementation and animal maintenance, was indicated by Mazzetto et al. (2015) as the main cause for this heterogeneity.

Capper (2012) and de Oliveira Silva et al. (2016) state that the prioritization of intensive cattle production strategies aimed at increasing feed conversion efficiency may attenuate enteric CH_4 emissions. De Vries et al. (2015) and Veysset et al. (2014) agree with this point of view, but warn that the procedure applied to decrease enteric CH_4 emissions should be extended to the life-cycle impacts of raw materials and inputs that integrate the alternatives under analysis.

Within the scope of animal production, it is also necessary to take into account pasture carbon capture potential to mitigate Climate Change impacts. Bustamante et al. (2006) observed that the average carbon sequestration potential of the air in well-managed pastures in the Cerrado Biome is of 1.30 t CO_2/year, reaching up to 3.00 t/year in some regions. Following the same approach, Maia et al. (2009) observed that carbon fixation ranges between 610 and 720 kg CO_2/year in non-degraded pastures from the Brazilian states of Mato Grosso (MT) and Rondônia (RO).

As the spatial density of the live load in the analyzed system is of 464 kg/ha (Florindo et al., 2017), each animal was estimated as occupying a 1.23 ha/year area. In view of the minimum and maximum carbon sequestration values described above, and a grazing period of three years, the area occupied by each cattle head was estimated as absorbing from 2.25 to 11.0 t CO_2 per production cycle.

If, according to the IPCC, the CO_2 impact factor for CC is IF = 1.00 kg $CO_{2\ eq}$/kg of emitted substance (IPCC, 2006), and admitting carbon absorption from the air as a 'negative contribution' to the impact, the consideration of this portion in the determination of the environmental performance of the Brazilian meat production would result in significant changes in the data. Under this approach, the product CF would be of 10.3 kg $CO_{2\ eq}$/kg boned meat for the most unfavorable situation (lower carbon uptake by pasture), and would reach (−) 19.8 kg $CO_{2\ eq}$/kg boned meat (higher uptakes than emissions), if the meadow metabolic activity were to reach maximum values for the region. For this reasoning to be extended to the rest of the country, its important to understand carbon dynamics in pasture soils in greater detail, as well as the carbon sequestration potential of these areas in other Brazilian regions (de Oliveira Silva et al., 2016).

Finally, with regard to transportion, the impacts generated by the system arise from diesel burning CO_2 emissions. Trans-oceanic mobility exhibits the lowest specific emissions (21 mg/km), followed by road transport from the slaughterhouse to the Port of Santos (35 mg/km) and from the farm to the slaughterhouse (81 mg/km). These results indicate an approximate four-fold variation between the most extreme performances, and more than

two-fold between land displacements.

Although the greatest CO_2 emission source, no alternatives that allow for potential improvements in live animal transport performance from the farm to the slaughterhouses are available. Regarding the journey between the slaughterhouses and Port of Santos, the option for intermodal transport (road vs. waterway) would provide significant decreases in the CO_2 emissions.

4.2. SWOT matrix

Fig. 2 describes the product of the result conversion process of the decision-making matrix into the SWOT matrix.

An analysis based on internal animal production criteria (Table 11 and Fig. 2) suggests that alternatives AP5 and AP8 did not have the expected effect on the process and, therefore, were not classified as either positive or negative. This reasoning is supported by the intermediate scores obtained by both proposals. AP2 (semi-confined system), AP3 (confined system) and AP7 (crop-livestock integration) appear as strengths for the CA1 and CA4 criteria. However, the same parameters, in contrast, expose AP1 (reference system) weaknesses. AP3 exhibited the highest response amplitude among the criteria, obtaining high scores in CA1 (9.00) and CA4 (9.75), but a minimum score in CA2 (3.45). Favorable attributes of the confined system include early animal slaughter and high production rate per hectare. Conversely, this technique establishes a high degree of dependence on non-renewable resources (fossil fuels) and electricity.

Most alternatives presented strengths when the production systems were observed externally, with two exceptions: AP2, which did not even relate to intermediate values in the external criteria; and AP3, whose unfavorable evaluations for CA3 and CA5 became the alternative with the greatest degree regarding implementation threat among the evaluated possibilities. In comparison to other systems, confinement demands high economic investments, lengthy consolidation periods, human resource training, and the use of machinery, besides being quite dependent on grains for food.

The analysis of the industrial stage for the internal criterion of energy efficiency (CI1) demonstrated that all proposed alternatives (IF1, IF2 and IF3) provided gains in relation to the original arrangement verified in this study. In this context, the use of renewable energies, which obtained a maximum CI1 score (9.58), is noteworthy. The proposals for replacing used vehicles for live animal transport and meat cooled by vehicles with higher carrying capacity (ITF2 and ITP2) achieved the lowest scores for the same criterion (6.67). The justification for both phenomena is based on the inverse correlation established between autonomy and diesel vehicle storage capacity. In terms of implementation costs (CI2), alternatives ITF1, ITF2 and ITP1 achieved favorable results, with ITF1 and ITP1 being listed as internal strengths for this criterion.

Animal production

	Strenghts		Weaknesses	
	Alternatives	Criteria	Alternatives	Criteria
Internal	AP1, AP4	CA2	AP1	CA1
	AP2, AP3, AP7	CA1	AP1	CA4
	AP2, AP3, AP7	CA4	AP3, AP7, AP8	CA2
	Opportunities		**Threats**	
	Alternatives	Criteria	Alternatives	Criteria
External	AP1, AP5, AP6, AP7, AP8	CA3	AP3	CA3
	AP1, AP4, AP5	CA5	AP3, AP7, AP8	CA5
	AP7, AP8	CA6		

(a)

Industry

	Strenghts		Weaknesses	
	Alternatives	Criteria	Alternatives	Criteria
Internal	IF3, ITP3	CI1	IF1, IF2, IF3, ITP3	CI2
	ITF1, ITP1	CI2		
	Opportunities		**Threats**	
	Alternatives	Criteria	Alternatives	Criteria
External	ITF1, ITF2, IF1, IF2, ITP1, ITP2, ITP3	CI4	IF1, IF3, ITP3	CI3
	ITF1, ITP1	CI3		

(b)

Fig. 2. SWOT matrix applied to: (a) stage of animal production; And (b) the industry stage of the beef production chain.

When explored under the same perspective, the other proposals reached lower scores (between 2.42 and 5.42), and are, therefore highly vulnerable in terms of potential implementation.

Regarding external criteria, all alternatives presented high scores in terms of the availability of financing lines (CI4), and were therefore classified as strengths, since. The industrial stage can rely on expressive financial contributions from banks, as improvement proposals are characterized as technological innovations.

IF1, IF2 and IF3 (in the slaughterhouse) and ITP3 (for multimodal transport) accumulated low scores in the criterion of restrictions regarding implementation (CI3). For the slaughterhouse, this is due to the need for temporary shutdown for improvement action implementations. In the case of multimodal transport, the discrete performance in CI3 is due to the obligation to adapt the transshipments to move refrigerated containers from the trucks to the freight trains.

The results achieved by the analysis demonstrate that the use of protein-energetic animal supplementation during livestock raising, or even pasture rotation fertilization are options displaying few implementation restrictions, but can lead to significant decreases in animal production. In the industrial stage, the replacement of transport vehicles provides positive results in terms of Climate Change precursor generation, with few execution limitations.

5. Conclusions and recommendations

This study presented a proposal for the joint application of MCDM techniques (Fuzzy Set Theory and TOPSIS) and Carbon Footprint to hierarchize possible improvement actions to be implemented in the Brazilian beef export process. These actions, which aim at reducing impacts in the form of Climate Changes, are based on evaluation criteria formulated from the identification of the impact profile associated with beef.

The results indicate that the animal production stage exhibits contributions that exceed 93% of the total GHG emissions of the system, regardless of the export destination. Regarding precursors, the CH_4 emissions generated due to animal enteric fermentation are significant. In the industrial stage, electricity use and transport activities appeared as the most important to be reevaluated in terms of GHG generation. The diversity of final destinations (Shanghai: CN; St. Petersburg: RU; and Rotterdam: NL) led to discrete variations (1.2–2.5%) in cumulative impacts, due to the inclusiveness of the trans-oceanic transport in comparison with internal displacements in the country, which were common for all the distribution routes.

During livestock raising, protein-energy supplementation systems, pasture rotation fertilization and crop-livestock integration appeared as potential potent alternatives for the reduction of GHG emissions. However, it is important to point out that, among the systems mentioned above, crop-livestock farming integration presented the highest scoring range of the evaluated criteria, being noteworthy as a promising alternative, also due to the existing potential for increased efficiency.

In the industrial stage, the need to pause activities to install more energy efficient equipment is a barrier to the adoption of improvement actions. Thus, the proposed solutions for this stage of the production chain were restricted to land transports. In this sense, the replacement of the fleets for live and refrigerated cargo displacement was presented as the best potential alternative to reduce GHG emissions.

A prospective analysis carried out with secondary data concluded that an adequate pasture management could reduce Climate Changes impacts associated with the beef production due to carbon sequestration from 10.3 to (−) 19.8 kg $CO_{2\ eq}$/kg boned meat. Therefore, a natural follow-up of this initiative would be a rigorous verification of the CO_2 absorption capacity of this raw material, which allows for the understanding of these dynamics in the different Brazilian grazing regions.

Beef is one of the main sources of animal protein in human diets. In addition, the beef production chain is consolidated in many countries, and is, therefore, an important source for the economic and social sustainability of those regions. In contrast, the product displays very high levels of Carbon Footprint. This controversial framework makes it necessary to implement actions that improve the environmental performance of this arrangement, to balance it with the other dimensions. Such advances will only be possible with synergic actions in two ways: academic research regarding the interface established between the productive process and its effects on the environment, and process management, also exercised by taking into account environmental variables.

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